SIM

CONTENTS

SIM

EXECUTIVE SUMMARY

Astrometry — the science of measuring the positions and thus distances and motions of celestial objects — is among the oldest branches of astronomy. At the threshold to the new millennium, the Space Interferometry Mission, known by its acronym SIM, is taking up the challenge to improve the accuracy of astrometric measurements several hundred times over our current capabilities. SIM, targeted for launch in 2005, is designed to achieve a global end-of-mission astrometric accuracy of 4 microarcseconds and a narrow-angle accuracy of 1 microarcsecond. The instrument making this precision possible is a Michelson interferometer with a 10-meter baseline, operating in the visible-light band. In addition to its exciting science program, SIM will also demonstrate optical synthesis imaging and nulling — key technologies for the astronomical observatories of the future.

Mature Science

The scientific justification for SIM has been in the making for centuries. Determining distances is among the most difficult measurements in astronomy. Because most of the observable parameters of the universe scale with distance, distances are also the most fundamental measurement in the universe. Our understanding of dynamics and kinematics scales linearly with distance, our measurements of the energy output of objects scale with the square of the distance, and our measurements of the masses of stars scale like the cube of the distance.

Even with recent advances, such as charge-coupled device (CCD) detectors providing parallaxes of increasingly faint objects and the dramatically successful Hipparcos mission, which has added enormous numbers of accurate distances, there is still a great sense of frustration: Truly accurate distances to objects much beyond 100 parsecs are rare to nonexistent. This frustration is amplified by the obvious success of Hipparcos and the sense that the solutions to so many classical problems are just beyond its reach.

A tenfold improvement in parallax accuracies would be revolutionary. SIM's expected nearly *thousandfold* improvement is almost unimaginable. On the shortest scales, luminosities of all the brightest stellar types and rare phases of stellar evolution would be calibrated. The expectation of high-precision, stellar seismology photometric measurements will require 0.5 percent or better distances for the relatively bright nearby stars. Currently, there are fewer than 10 objects brighter than 6 magnitude that satisfy that criterion.

Beyond that, the process of confronting stellar-evolution calculations with the corresponding observations will move to a new plane. One-percent distances to literally dozens of open clusters and association members will be available, covering the complete range of ages and metallicities. Three-percent distances to 10 globular clusters covering most of their range of properties are expected. Besides extending the confrontation with theory, the reduction in the uncertainty of the deduced ages of the globular clusters will shed light on the formation of our Milky Way Galaxy and sharpen the disagreement (or eliminate it) between various estimates of the age of the universe.

SIM's capabilities are ideally suited to the study of the Milky Way.

On larger scales, SIM's capabilities are ideally suited to the study of the Milky Way. Distances accurate to 10 percent can be determined out to 25,000 parsecs, essentially covering our galaxy. Proper motions will be determined with an accuracy corresponding to an uncertainty of 10 meters per second out to 1 kiloparsec. All the fundamental properties of our galaxy will be subject to SIM's scrutiny: the distance to the center, the scales and kinematics of the halo, the extent and figure of the recently discovered central bar, and the amount and distribution of the "dark matter" component. To this end, determining the exact shape and dynamics of another recent discovery — the Sagittarius dwarf spheroidal galaxy currently plunging through the plane of the Milky Way on the far side — will provide an extremely sensitive measurement of mass and mass accretion history.

The Milky Way's nearby companions will also be accessible. These include the entire globular cluster system and the various satellite dwarf galaxies, including the Large and Small Magellanic Clouds. Although too far away to allow accurate distance measurements in most cases, the proper motions of the systems will put strong limits on the amount of mass out to 100 kiloparsecs. In turn, measurements of the proper motions of members of a few of the dwarf spheroidal galaxies will reveal the extent to which they are dominated by dark matter.

SIM AT A GLANCE

The Space Interferometry Mission instrument is a space-based, 10-meter baseline optical Michelson interferometer. In wide-angle mode, SIM will be capable of providing 4-microarcsecond precision absolute-position measurements of stars — with parallaxes to comparable accuracy — at the end of a 5-year mission. The expected proper-motion accuracy is about 2 microarcseconds per year, corresponding to a transverse velocity of 10 meters per second at a distance of 1 kiloparsec. In narrow-angle mode (1-microarcsecond accuracy), SIM will search for planetary companions to nearby stars by detecting their astrometric "wobble."

Within each "tile" of a 15-degree-wide field of regard, SIM will take multiple relative measurements of the separations of "grid stars." Wide-angle astrometry is performed by combining the relative positions of the grid stars in overlapping tiles and constructing an astrometric grid covering the entire sky.

SIM is being developed by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration (NASA), in close collaboration with two industry partners — Lockheed Martin Missiles and Space in Sunnyvale, California, and TRW Inc., Space and Electronics Group, in Redondo Beach, California.

SIM INSTRUMENT AND MISSION PARAMETERS

Baseline	10 m
Wavelength range	0.4 – 0.9 μm
Telescope aperture	0.3 m diameter
Astrometric field of regard	15°
Astrometric narrow-angle field of view	1°
Imaging field of view	0.3 arcsec
Orbit	Heliocentric Earth-trailing
Mission life	5 years (launch mid-2005)
Wide-angle end-of-mission accuracy	4 μas
Astrometry sensitivity	20 mag in 4 hr
Narrow-angle accuracy	1 μas
Imaging resolution	10 milliarcsec
Imaging sensitivity (point source)	20 mag in 1 hr
Interferometric nulling	Null depth 10^{-4}

Finally, on still larger scales, measuring the rotation of a number of nearby spirals, notably the Andromeda galaxy, should provide accurate distances to these systems free of all the biases associated with photometric methods. These galaxies themselves, as well as the Cepheid stars and other giant stars they harbor, will provide calibrations of these "standard candles," bypassing a large number of intermediate steps and their attendant uncertainties. Studies of the transverse motions of a few galaxies outside the Local Group will measure directly the randomness superimposed on the Hubble expansion.

Buried in the details of the instrument's capabilities is the ability to measure the angle between two objects another factor of two to four better if the objects are not separated by more than a degree or so. This so-called "narrow-angle" capability provides a major step up in our quest to detect planets around other suns and to understand the planet-building process.

SIM will have the capability to detect Earth-mass objects in 1–astronomical unit (AU) orbits around the nearest two or three stars, should such bodies exist, through the reflex motions of the stars themselves. Beyond that, SIM will be able to search for "massive Earths" around a significant number of stars and for Jupiters around stars up to a kiloparsec distant. The detections would include determining the inclination of the orbits and would hence also provide the masses of the planets. This capability would improve by a factor of 10 to 20 the capability that is projected for the Keck Interferometer.

All this, described more completely in the following sections — and much more — constitutes an extraordinarily rich scientific justification, which will leave virtually no part of astronomy untouched and which alone justifies this remarkable mission.

Essential Technology

When it comes to space hardware, technology pathfinders are never cheap, particularly when the technology demonstration involves launching a significant instrument. The optimum is to mate a demonstration of essential technology with an unassailable piece of science. This is the case with SIM.

The technologies to be demonstrated occur on several levels. An important goal is to demonstrate synthesis imaging with an optical Michelson interferometer in space. By SIM standards, this is relatively simple and can be accomplished by showing an acceptable synthesis of simple images with moderate dynamic range. This would be analogous to radio synthesis, before adoption of "closure phase" techniques, with two apertures. The vibration suppression and isolation, and the metrology required by the astrometric science described above, exceed those required by simple imaging by an order of magnitude.

SIM represents a new dimension of potential solutions to difficult observational questions.

Because of this, for otherwise uncomplicated images, dynamic range should approach that of multi-aperture systems capable of enforcing phase closure. Beyond this, for little additional cost SIM will carry a nulling experiment. A null depth of one part in ten thousand in the optical places the same absolute demands on pathlength control and metrology as a null depth of 1 part in 1 million in the infrared would require. Such a null depth is required for the proposed Terrestrial Planet Finder (TPF). Combined with the critical step that SIM will take in the search for Earth-class planets, it is clear that SIM is directly on the path to the TPF mission.

Unique Legacy

The real legacy of the Space Interferometry Mission will be the first demonstration of the remarkable capabilities of optical interferometry in a major scientific instrument in space. With a two-mirror system, the primary demonstration is the science enabled by extraordinary dimensional stability and precision metrology. In addition, the ability to null over a finite field to several orders of magnitude provides a unique capability, the potential of which may take some time to fully appreciate.

What about the future? Besides the obvious gains associated with the potential to increase mirror size and baseline, the ability to incorporate additional apertures at different separations into the synthesized focal plane provides a whole new dimension of capabilities and potential solutions to difficult observational questions.

Even now, several obvious extensions are being explored. One set of ideas expands on the linear geometry of the classical Michelson interferometer, adding elements along the optical axis. By varying aperture sizes, one may tailor to some extent the shape and depth of the null. In this way, the effort to detect and analyze the light from planetary companions to a fairly large number of nearby stars becomes feasible.

And what do we do once we have detected and characterized the atmospheres of planets orbiting a number of nearby stars? One answer: make images. This is a formidable challenge. Even a goal as modest as resolving an Earth-size planet at 10 parsecs

TRACING SIM TO THE BAHCALL REPORT

The foundation of the SIM science objectives is firmly rooted in the recommendations of the last Astronomy and Astrophysics Survey Committee (1991 Bahcall Report). The report recommended an astrometric interferometry mission as a high priority for the 1990s possessing the following attributes (from page 85 of the report):

"The mission requirement would be to measure positions of widely separated objects to a visual magnitude of 20 with a precision of 30 millionths of an arcsecond; a more challenging goal would be to measure the positions with a precision of 3 millionths of an arcsecond."

SIM's requirement is to perform global astrometry at the level of 4 millionths of an arcsecond, which is at the most stringent end of the recommended range.

"The [mission] … would permit definite searches for planets around stars as far away as 500 light-years through the wobbles of the parent stars …"

SIM's requirement is to perform narrow-angle astrometry at the level of 1 mas, which permits detection of Jupiter-mass planets many thousands of light-years away, and planets with masses as small as a few Earths around nearby stars.

"[The mission would permit] … trigonometric determination of distances throughout the Galaxy …"

SIM will be able to directly measure distances via parallax to better than 10 percent anywhere in the Galaxy. Furthermore, SIM will put the cosmic distance scale on solid footing by directly calibrating the luminosity of Cepheids.

"[The mission] would demonstrate the technology required for future [interferometry] space missions."

SIM serves as the technology pathfinder for the future Terrestrial Planet Finder (TPF) by specifically addressing some of the most challenging technological needs of TPF.

by a factor of 10 (10 pixels across a diameter) requires baselines 10^5 times that needed to detect the planet and almost a hundredfold increase in collecting area (operating at 10 micrometers). Still, given Earth as an example, this would show up the continents and oceans unambiguously, as well as demonstrating seasonal polar cap variations. The rewards of such a discovery would be monumental.

The immediate problem continues to be that imposed by the star's light. A possible solution would involve an array of TPF-style instruments, all feeding the nulled beams to a central beam combiner for a full synthesis of the system surrounding the central star. Approximately 100 square meters of collecting area total and an outer baseline of the order of 2,400 kilometers would be required. Baselines would scale linearly for higher resolution, while the aperture required would increase as the third or fourth power. While daunting, such an effort can be contemplated and might even be deliverable within a cost that society would be willing to support.

Path to Revolutionary Discoveries

We have not begun to look at all the science areas where the application of large-scale interferometry, outside the confines of the Earth's atmosphere, are unambiguously required. For example, as we continue to probe the farthest edges of the observable universe to smaller and smaller scales and to fainter and fainter signal levels, it is difficult to conceive of the instruments as monolithic light collectors. Eventually, the realities of constructing and launching instruments with large amounts of light-collecting area, and at the same time providing optimal resolution, will force instruments toward dilute apertures, i.e., interferometers. Even now, designs for the Next-Generation Space Telescope instrument are leaning toward mostly filled apertures with segmented elements composing the mirrors — all of which require real-time phasing. It is difficult to define exactly at what point such instruments cease being called "mirrors" and become more appropriately "interferometers." The Space Interferometry Mission will be the first of these instruments opening a path to truly revolutionary discoveries.